

PATENT CLAIMS:

1. A polarization-modulating optical element which has a
5 thickness profile or comprises a thickness profile and
consists of or comprises an optically active crystal with
an optical axis, wherein the thickness profile, as
measured in the direction of the optical axis, is
variable.
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2. The polarization-modulating optical element according to
claim 1, wherein respective planes of oscillation of a
first linearly polarized light ray and a second linearly
15 polarized light ray are rotated, respectively, by a first
angle of rotation and a second angle of rotation in such a
way that the first angle of rotation is different from the
second angle of rotation.
3. The polarization-modulating optical element according to
20 claim 1 or 2, wherein the optically active crystal is
quartz, TeO_2 or AgGaS_2 .
4. The polarization-modulating optical element according to
one of the claims 1 to 3, wherein the polarization-
25 modulating optical element transforms an entering light
bundle with a first linear polarization distribution into
an exiting light bundle with a second linear polarization
distribution, and wherein the first linear polarization
distribution is different from the second linear
30 polarization distribution.
5. The polarization-modulating optical element according to
claim 4, wherein the polarization distribution of the

exiting light bundle is an approximately tangential polarization distribution.

6. The polarization-modulating optical element according to claim 4, wherein the polarization distribution of the exiting light bundle is an approximately radial polarization distribution.

7. The polarization-modulating optical element according to one of the claims 1 to 6, wherein the polarization-modulating optical element has an element axis oriented substantially in the direction of the optical axis of the optically active crystal, and wherein the thickness profile in relation to the element axis has a variation that depends only on an azimuth angle θ , said azimuth angle θ being measured from a reference axis that runs perpendicular to the element axis and intersects the element axis.

8. The polarization-modulating optical element according to claim 7, wherein the thickness profile has a constant value along a radius that is oriented perpendicularly to the element axis and at an angle θ relative to the reference axis.

9. The polarization-modulating optical element according to claim 7 or 8, wherein an azimuthal section $d(r=\text{const.}, \theta)$ of the thickness profile $d(r, \theta)$ in a range of azimuth angles $10^\circ < \theta < 350^\circ$ and at a constant distance r from the element axis is a linear function of the azimuth angle θ , wherein this azimuthal section has a slope m conforming approximately to the expression $|m| = \frac{180^\circ}{\alpha \pi r}$, with α

representing the specific rotation of the optically active crystal.

10. The polarization-modulating optical element according to
5 claim 9, wherein the azimuthal section $d(r=\text{const.}, \theta)$ has a substantially jump-like increase of $360^\circ/\alpha$ at the azimuth angle $\theta=0^\circ$.

10 11. The polarization-modulating optical element according to claim 7 or 8, wherein an azimuthal section $d(r=\text{const.}, \theta)$ of the thickness profile $d(r, \theta)$ in a range of azimuth angles $10^\circ < \theta < 170^\circ$ and $190^\circ < \theta < 350^\circ$ at a constant distance r from the element axis is a linear function of the azimuth angle θ , wherein this azimuthal section has a
15 slope m conforming approximately to the expression

$|m| = \frac{180^\circ}{\alpha n r}$, with α representing the specific rotation of the optically active crystal.

12. The polarization-modulating optical element according to
20 claim 11, wherein the azimuthal section $d(r=\text{const.}, \theta)$ has a substantially jump-like increase of $180^\circ/\alpha$ at the azimuth angles $\theta=0^\circ$ and $\theta=180^\circ$.

13. The polarization-modulating optical element according to
25 claim 7 or 8, wherein an azimuthal section $d(r=\text{const.}, \theta)$ of the thickness profile $d(r, \theta)$ at a constant distance r from the element axis and in a first azimuth angle range of $10^\circ < \theta < 170^\circ$ is a linear function of the azimuth angle θ with a first slope m , while in a second azimuth angle
30 range of $190^\circ < \theta < 350^\circ$, the azimuthal section is a linear function of the azimuth angle θ with a second slope n , wherein the slopes m and n have the same absolute magnitude but opposite signs, and wherein the magnitude of

the slopes m and n conforms to the expression $|m| = |n| = \frac{180^\circ}{\alpha n r}$ with α representing the specific rotation of the optically active crystal.

14. The polarization-modulating optical element according to one of the claims 1 to 8, wherein the polarization-modulating optical element consists of or comprises at least two planar-parallel portions of different thickness or different optical effective thickness .

15. The polarization-modulating optical element according to claim 14, wherein said portions are configured as sectors of a circle, or as hexagonal, square, rectangular, or trapeze-shaped raster elements and/or comprise at least a cuvette comprising an optically active or optically inactive liquid.

16. The polarization-modulating optical element according to claim 14 or 15, wherein a pair of first plan-parallel portions are arranged on opposite sides of a central element axis of said polarization-modulating optical element, and wherein a pair of second plan-parallel portions are arranged on opposite sides of said element axis and circumferentially displaced around said element axis with respect to said first plan-parallel portions, wherein each of said first portions has a thickness or optical effective thickness being different from a thickness or optical effective thickness of each of said second portions.

17. The polarization-modulating optical element according to claim 16, wherein a plane of oscillation of linearly polarized light passing there through is rotated

by a first angle of rotation β_1 within at least one of said first plan-parallel portions and by a second angle of rotation β_2 within at least one of said second plan-parallel portions, such that β_1 and β_2 are approximately conforming to the expression $|\beta_2 - \beta_1| = (2n+1) \cdot 90^\circ$, with n representing an integer.

18. The polarization-modulating optical element according to claim 17, wherein β_1 and β_2 are approximately conforming to the expressions $\beta_1 = 90^\circ + p \cdot 180^\circ$, with p representing an integer, and $\beta_2 = q \cdot 180^\circ$, with q representing an integer other than zero.

19. The polarization-modulating optical element according to anyone of the claims 16 to 18, wherein said pair of second plan-parallel portions is circumferentially displaced around said element axis with respect to said pair of first plan-parallel portions by approximately 90° .

20. The polarization-modulating optical element according to anyone of the claims 16 to 19, wherein said pair of first plan-parallel portions and said pair of second plan-parallel portions are arranged on opposite sides of a central opening or a central obscuration of said polarization-modulating optical element.

21. The polarization-modulating optical element according to anyone of the claims 16 to 20, wherein adjacent portions of said first and second pairs are spaced apart from each other by regions being opaque or not optically active to linearly polarized light entering said polarization-modulating optical element.

22. The polarization-modulating optical element
according to claim 16 to 21, wherein said portions of
said first and second group are held together by a
mounting.
23. The polarization-modulating optical element
according to claim 22, wherein said mounting is opaque or
not optically active to linearly polarized light entering
said polarization-modulating optical element.
24. The polarization-modulating optical element
according to claim 22 or 23, wherein said mounting has a
substantially spoke-wheel shape.
25. The polarization-modulating optical element
according to anyone of the claims 14 to 24, comprising a
first group of substantially planar-parallel portions
wherein a plane of oscillation of traversing linearly
polarized light is rotated by a first angle of rotation
 β_1 , and a second group of substantially planar-parallel
portions wherein a plane of oscillation of traversing
linearly polarized light is rotated by a second angle of
rotation, such that β_1 and β_2 are approximately conforming
to the expression $|\beta_2 - \beta_1| = (2n+1) \cdot 90^\circ$, with n representing
an integer.
26. The polarization-modulating optical element
according to claim 25, wherein β_1 and β_2 are approximately
conforming to the expressions $\beta_1 = 90^\circ + p \cdot 180^\circ$, with p
representing an integer, and $\beta_2 = q \cdot 180^\circ$, with q
representing an integer other than zero.

27. The polarization-modulating optical element according to one of the claims 1 to 8, wherein the thickness profile or profile of effective optical thickness has a continuous shape.
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28. The polarization-modulating optical element according to one of the claims 1 to 27, further having an element diameter D and a minimal thickness d_{\min} , wherein the minimal thickness d_{\min} is at least equal to 0.002 times the element diameter D.
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29. The polarization-modulating optical element according to one of the claims 1 to 28, wherein the thickness profile has a minimal thickness $d_{\min} = N \cdot \frac{90^\circ}{\alpha}$, with α representing the specific rotation of the optically active crystal and N representing a positive integer.
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30. The polarization-modulating optical element according to one of the claims 1 to 29, wherein the polarization-modulating optical element has a central opening or a central obscuration.
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31. The polarization-modulating optical element according to one of the claims 1 to 30, wherein the polarization-modulating optical element transforms an entering light bundle with a first polarization distribution into an exiting light bundle with a second polarization distribution, wherein the entering light bundle consists of a multitude of light rays with an angle distribution relative to the optical axis of the optically active crystal, and wherein the angle
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distribution has a maximum angle of incidence not exceeding 100 mrad.

32. A polarization-modulating optical element, wherein
5 the plane of oscillation of a first linearly polarized
light ray and the plane of oscillation of a second
linearly polarized light ray are rotated, respectively,
by a first angle of rotation and a second angle of
rotation in such a way that the first angle of rotation
10 is different from the second angle of rotation, and
wherein the polarization-modulating optical element
consists of an optically active material or comprises an
optically active material.

15 33. The polarization-modulating optical element
according to claim 32, comprising at least two planar-
parallel portions of different thickness, or different
effective optical thickness.

20 34. The polarization-modulating optical element
according to claim 33, wherein said portions are
configured as sectors of a circle, or as hexagonal,
square, rectangular, or trapeze-shaped raster elements,
or wherein said portions comprises at least one cuvette
25 with an optically active or optically inactive liquid.

35. The polarization-modulating optical element
according to claim 33 or 34, wherein a pair of first
plan-parallel portions are arranged on opposite sides of
30 a central element axis of said polarization-modulating
optical element, and wherein a pair of second plan-
parallel portions are arranged on opposite sides of said
element axis and circumferentially displaced around said
element axis with respect to said first plan-parallel

portions, wherein each of said first portions has a thickness or effective optical thickness being different from a thickness or effective optical thickness of each of said second portions.

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36. The polarization-modulating optical element according to claim 35, wherein a plane of oscillation of linearly polarized light passing therethrough is rotated by a first angle of rotation β_1 within at least one of said first plan-parallel portions and by a second angle of rotation β_2 within at least one of said second plan-parallel portions, such that β_1 and β_2 are approximately conforming to the expression $|\beta_2 - \beta_1| = (2n+1) \cdot 90^\circ$, with n representing an integer.

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37. The polarization-modulating optical element according to claim 36, wherein β_1 and β_2 are approximately conforming to the expressions $\beta_1 = 90^\circ + p \cdot 180^\circ$, with p representing an integer, and $\beta_2 = q \cdot 180^\circ$, with q representing an integer other than zero.

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38. The polarization-modulating optical element according to anyone of the claims 35 to 37, wherein said pair of second plan-parallel portions is circumferentially displaced around said element axis with respect to said pair of first plan-parallel portions by approximately 90° .

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39. The polarization-modulating optical element according to anyone of the claims 35 to 38, wherein said pair of first plan-parallel portions and said pair of second plan-parallel portions are arranged on opposite

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sides of a central opening or a central obscuration of said polarization-modulating optical element.

40. The polarization-modulating optical element
5 according to anyone of the claims 35 to 39, wherein adjacent portions of said first and second pairs are spaced apart from each other by regions being opaque or not optically active to linearly polarized light entering said polarization-modulating optical element.
- 10 41. The polarization-modulating optical element according to claim 35 to 40, wherein said portions of said first and second group are held together by a mounting.
- 15 42. The polarization-modulating optical element according to claim 41, wherein said mounting is opaque or not optically active to linearly polarized light entering said polarization-modulating optical element.
- 20 43. The polarization-modulating optical element according to claim 41 or 42, wherein said mounting has a substantially spoke-wheel shape.
- 25 44. The polarization-modulating optical element according to anyone of the claims 33 to 43, comprising a first group of substantially planar-parallel portions wherein a plane of oscillation of traversing linearly polarized light is rotated by a first angle of rotation
30 β_1 , and a second group of substantially planar-parallel portions wherein a plane of oscillation of traversing linearly polarized light is rotated by a second angle of rotation, such that β_1 and β_2 are approximately conforming

to the expression $|\beta_2 - \beta_1| = (2n+1) \cdot 90^\circ$, with n representing an integer.

45. The polarization-modulating optical element
5 according to claim 44, wherein β_1 and β_2 are approximately conforming to the expressions $\beta_1 = 90^\circ + p \cdot 180^\circ$, with p representing an integer, and $\beta_2 = q \cdot 180^\circ$, with q representing an integer other than zero

10 46. An optical arrangement with a polarization-modulating optical element according to one of the claims 1 to 45, wherein the optical arrangement is configured so that at least one further polarization-modulating optical element can be put into the light path.

15 47. The optical arrangement of claim 46, wherein the further polarization-modulating optical element comprises a polarization-modulating optical element in accordance with at least one of the claims 1 to 45.

20 48. The optical arrangement of claim 46, wherein the further polarization-modulating optical element comprises a planar-parallel plate of an optically active crystal and/or a cuvette with optically active or optically
25 inactive liquid.

49. The optical arrangement of claim 46, wherein the further polarization-modulating optical element comprises a rotator made of two half-wavelength plates that are
30 rotated by 45° relative to each other.

50. The optical arrangement of claim 46, wherein the polarization-modulating optical element has an element axis in reference to which the thickness profile has a

variation that depends only on an azimuth angle θ , wherein the azimuth angle θ is measured from a reference axis that is oriented perpendicular to the element axis and intersects the element axis, wherein the thickness profile in a first azimuth angle range of $10^\circ < \theta < 170^\circ$ is a linear function of the azimuth angle θ with a first slope m , while in a second azimuth angle range of $190^\circ < \theta < 350^\circ$ the azimuthal section is a linear function of the azimuth angle θ with a second slope n , wherein the slopes m and n have the same absolute magnitude but opposite signs, and wherein the further polarization-modulating optical element comprises a planar-parallel plate which is configured as a half-wavelength plate for a half-space that covers an azimuth-angle range of 180° .

51. The optical arrangement of claim 46, wherein the further polarization-modulating optical element causes a 90° -rotation of the oscillation plane of a linearly polarized light ray passing through said optical arrangement.
52. The optical arrangement according to anyone of the claims 46 to 51, wherein a compensation plate is arranged in the light path of the optical system, said compensation plate having a thickness profile configured to substantially compensate the angle deviations of transmitted radiation which are caused by the polarization-modulating optical element.
53. A projection system, comprising a radiation source, an illumination system operable to illuminate a structured mask, and a projection objective for projecting an image of the mask structure onto a light-sensitive substrate, wherein the polarization-modulating

optical element according to one of the claims 1 to 45 is arranged in the illumination system.

54. The projection system according to claim 53, wherein
5 an optical arrangement according to one of the claims 46 to 52 is arranged in the illumination system.

55. The projection system according to claim 53 or claim
10 54, wherein an immersion medium with a refractive index different from air is present between the substrate and the optical element nearest to the substrate.

56. Method of manufacturing micro-structured
15 semiconductor components, comprising the step of using a projection system in accordance with one of the claims 53 to 55.

57. An optical system comprising an optical axis or a
20 preferred direction given by the direction of a light beam propagating through the optical system, the optical system comprising a polarization-modulating optical element described by coordinates of a coordinate system, wherein one preferred coordinate of the coordinate system is parallel to the optical axis or parallel to said
25 preferred direction, the polarization-modulating optical element comprises optical active material and a profile of effective optical thickness, wherein the effective optical thickness varies at least as a function of one coordinate different from the preferred coordinate of the
30 coordinate system.

58. The optical system of claim 57, wherein the effective optical thickness varies due to variations of the specific rotation of the polarization-modulating

optical element.

59. The optical system of claim 57, wherein the effective optical thickness varies due to variations of the geometrical thickness of the polarization-modulating optical element.

60. The optical system according to one of the claims 57 to 59, wherein the polarization-modulating optical element comprises an optically active or an optically inactive liquid and/or an optically active crystal.

61. The optical system according to one of the claims 57 to 60, wherein the polarization-modulating optical element comprises clockwise and counterclockwise optically active materials.

62. The optical system according to one of the claims 57 to 61, wherein respective planes of oscillation of a first linearly polarized light ray and a second linearly polarized light ray, both propagating through the optical system and passing the polarization-modulating optical element with different paths, are rotated by a respective first and second angle of rotation such that the first angle is different of the second angle.

63. The optical system according to one of the claims 57 to 62, wherein the polarization-modulating optical element transforms a light bundle with a first linear polarization distribution, entering said polarization-modulating optical element, into a light bundle exiting said polarization-modulating optical element and having a second linear polarization distribution, wherein the second linear polarization distribution is different from

the first linear polarization distribution.

64. The optical system according to one of the claims 57 to 63, comprising a polarization control system for controlling the polarization distribution of the light beam, propagating through the optical system, at a predefined location in the optical system, the polarization control system comprises at least one heating or cooling device to modify the temperature and/or the temperature distribution of the polarization-modulating optical element to affect the polarization distribution of the light beam at the predefined location in the optical system.

65. An optical system comprising an optical axis or a preferred direction given by the direction of a light beam propagating through the optical system, the optical system comprising a polarization-modulating optical element described by coordinates of a coordinate system, wherein one preferred coordinate of the coordinate system is parallel to the optical axis or parallel to said preferred direction, the polarization-modulating optical element comprises solid and/or liquid optically active material, wherein the effective optical thickness is constant as a function of at least one coordinate different from the preferred coordinate of the coordinate system, the optical system comprises further a polarization control system for controlling the polarization distribution of the light beam, propagating through the optical system, at a predefined location in the optical system, the polarization control system comprises at least one heating or cooling device to modify the temperature and/or the temperature distribution of the polarization-modulating optical

element to affect the polarization distribution of the light beam at the predefined location in the optical system.

5 66. The optical system according to claim 65, wherein
the solid and/or liquid optically active material is a
parallel plate or has the form of it, comprising
optically active quartz with its optical axis parallel to
the optical axis of the optical system or parallel to the
10 preferred direction of the optical system.

67. The optical system according to one of the claims 64
to 66, wherein the polarization control system comprises
15 at least one temperature sensor providing a temperature
sensor value representative for or equal to the
temperature and/or the temperature distribution of the
polarization-modulating optical element, a control
circuit to control the at least one heating or cooling
20 device dependent on said temperature sensor value by open
or closed loop control.

68. The optical system according to claim 67, wherein
the polarization control system comprises a polarization
25 measuring device providing a polarization value
representative for or equal to the polarization or the
polarization distribution of the light beam at the
predefined location in the optical system, and the
control circuit controls the at least one heating or
30 cooling device dependent on said temperature sensor value
and/or said polarization value by open or closed loop
control.

69. The optical system according to one of the claims 67 to 68, wherein the control circuit comprises a computer system or is connected to a computer system.

5 70. The optical system according to one of the claims 64 to 69, comprising at least one additional optical element arranged between the polarization-modulating optical element and the predefined location in the optical system such that the light beam contacts the at least one
10 additional optical element when propagating from the polarization-modulating optical element to the predefined location in the optical system.

15 71. The optical system according to claim 70, wherein the additional optical element comprises a lens, a prism, a mirror, a refractive or a diffractive optical element or an optical element comprising linear birefringent material.

20 72. The optical system according to one of the claims 57 to 71, wherein the polarization-modulating optical element comprises the polarization-modulating optical element in accordance with at least one of the claims 1 to 45.

25 73. The optical system according to one of the claims 57 to 71, wherein the polarization-modulating optical element comprises a parallel plate, the plate comprising optically active quartz with its optical axis parallel to
30 the optical axis of the optical system or parallel to the preferred direction of the optical system.

74. The optical system according to one of the claims 64 to 73, wherein the heating device comprises at least one

infrared heater and/or at least one Peltier device arranged such that the infrared heater and the Peltier device is not in the optical path of the light beam propagating through the optical system.

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75. An optical system comprising an optical axis or a preferred direction given by the direction of a light beam propagating through the optical system, the optical system comprising a temperature compensated polarization-modulating optical element described by coordinates of a coordinate system, wherein one preferred coordinate of the coordinate system is parallel to the optical axis or parallel to said preferred direction, the temperature compensated polarization-modulating optical element comprises a first and a second polarization-modulating optical element, the first and/or the second polarization-modulating optical element comprising solid and/or liquid optically active material and a profile of effective optical thickness, wherein the effective optical thickness varies at least as a function of one coordinate different from the preferred coordinate of the coordinate system, in addition or alternative the first and/or the second polarization-modulating optical element comprises solid and/or liquid optically active material, wherein the effective optical thickness is constant as a function of at least one coordinate different from the preferred coordinate of the coordinate system, wherein the first and the second polarization-modulating optical elements comprise optically active materials with specific rotations of opposite signs, or wherein the first polarization-modulating optical element comprises optically active material with a specific rotation of opposite sign compared to the optically active material

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of the second polarization-modulating optical element.

76. The optical system of claim 76, wherein the first and the second polarization-modulating optical elements are plane plates with a first and a second thickness in the direction of the propagating light beam, the plates are made of optically active quartz with clockwise and counterclockwise specific rotation.

77. The optical system of claim 76, wherein the absolute value of the difference of the first and the second thickness is smaller than the thickness of the smaller plate.

78. The optical system in accordance of one of the claims 57 to 77, wherein at least one polarization-modulating optical element comprises optically active or inactive material which is subjected to a magnetic field with a field component parallel to the direction of the light beam propagating through the polarization-modulating optical element.

79. A projection system, comprising a radiation source, an illumination system operable to illuminate a structured mask, and a projection objective for projecting an image of the mask structure onto a light-sensitive substrate, and comprising the optical system according to one of the claims 57 to 78.

80. The projection system according to claim 79, wherein an immersion medium with a refractive index different from air is present between the substrate and the optical element nearest to the substrate.

81. Method of manufacturing micro-structured semiconductor components, comprising the step of using a projection system in accordance with one of the claims 79 or 80.